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Energy and Exergy Analysis of raw material Preparation in a cement production plant

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ABSTRACT

The production process of a major wet process cement manufacturing plant in Nigeria was studied and data collected for a five year period 2001 – 2005, from them enabled the estimation of the embodied energy intensity, exergy efficiency and the environmental impact of the raw material preparation process was assessed. The cement plant accounts for over 40% of total local production of cement in Nigeria. The Input – Output energy analysis methodology was used to evaluate the embodied energy intensity which was found to decrease over the period by 35% from 91.7 kWh/t to 57.6kWh/t, this embodied intensity was over 70% higher than the best recommended global practice of 18 – 20kWh/t. Exergy analysis was used to evaluate the exergy efficiency of the raw material preparation and this increased marginally from 45 – 49% over the period, compared to best global practices of 50% this was found to be optimum. CO_2 and CO are two major greenhouse gas emitted during the raw material preparation process, however there was a 20% reduction in their emission over the study period.

Key words: Embodied Energy, Exergy Efficiency, and environmental impact.

INTRODUCTION

Energy, the ability to accomplish physical work or to produce heat is an input for economic and industrial processes and an intermediate good. It is a strategic commodity that promotes economic growth through industrialization and exportation of manufactured goods. The relevance of energy in the process of economic development has led to the questioning of the neo – classical production function where land, labour, and capital are recognized as the main factors of production [1].

Energy analysis is the aspect of energy study that is involved in the measurement of the energy content of manufactured products as one statistical input to industrial management decisions. It seeks to trace and quantify not only the readily recognizable and measureable direct energy input to a process or a product but also the upstream indirect energy inputs. Energy analysis of a system will not only identify the energy consumption by system and fuel type, but will also describe the efficiency of all sub – systems in a system. It is also expected to identify operation scheduling and maintenance efficiency opportunities as well as identifying opportunities for engineered energy efficiency solutions.

Exergy is defined as the maximum amount of work, which can be produced by a system. It is a measure of the potential of the system. Unlike energy, exergy is not subject to a conservation law, thus exergy is consumed or destroyed, due to irreversibilities in any real process. Exergy analysis is a tool for tracing the useful portion of the energy flowing through a system. Energy analysis alone can often be misleading as energy can be transformed to many forms with different levels of quality. An exergetic analysis of a system helps identify primary sources of loss and provides a more accurate picture of the performance relative to the theoretical ideal.

In this study, energy and exergy analysis of a raw material preparation unit in a wet process cement plant in south – western Nigeria were performed for estimating the embodied energy intensity, exergy efficiency and the environmental impact of its raw material preparation process.

The structure of the paper is organized as follows: section 1 includes the introduction. The description of the raw material preparation process of cement production and an overview of the selected cement manufacturing plant is given in section 2. Energy and exergy analysis method utilized in the study is discussed in section 3. Section 4 discusses the results obtained, while section 5 concludes.

RAW MATERIAL PREPARATION PROCESS

The principal steps in the raw material preparation process of cement production are: quarrying, Limestone crushing and raw stone pilling; and raw milling.

Raw material for the cement industry is usually obtained by large – scale open – cast quarrying operations. Drilling and blasting are the favoured combination for breaking out material, while the large – hole blasting method or well – drill blasting is the predominant method for dislodging the rock surface. The method brings down large masses of rock from the face suitably fragmented for loading. Boulders are usually broken up by secondary blasting, which gives a suitably fragmented product, whatever the type of rock. This is done by drilling small – diameter holes to a depth equal to a little more than the diameter of the boulder. They are charged with 60 – 90g of explosives per m^3 of rock, stemmed and electrically detonated.

Solid rock material dislodged from its natural deposit by blasting forms a coarsely fragmented rock pile, which has to be reduced to a fine powder in order to produce a homogenous mixture, which will quickly be converted in the kiln into a homogenous clinker containing no free lime. As a rule, size reduction of the raw material is affected in at least two main stages: crushing (primary reduction) and grinding (fine reduction). Crushing denotes the size reduction process that breaks down the material to a particle size suitable as feed for the next main stage, grinding. Crushing reduces the particle size to between about 80 and 200mm. This crushed product is further reduced by grinding to fineness below about 0.2mm size.

The crushed limestone is stockpiled to reduce day – to – day variation in the chemical characteristics of the raw material and also provides buffer stock (at least one week's kiln feed, to be used between intermittent quarrying and crushing operations) to maintain continuous raw milling. Another step in the stockpiling stage is to blend two or more materials to obtain desired characteristics. After stockpiling is the raw milling stage, in which the raw material is grounded to a powder fine enough (up to 15% residue captured on a 90mm sieve) to burn in the kiln.

The raw material for cement manufacture has a $CaCO_3$ content between about 74 and 79% by weight; sometimes this limestone contain a certain amount of dolomite $CaMg\ (CO_3)_2$ and thus introduce magnesium oxide (MgO) into the raw material. If it is not possible to obtain the desired chemical composition from these two materials, it will be necessary to add relatively small quantities of corrective ingredients to the mix. The objective of adding these corrective ingredients are to adjust the chemical composition of the raw mix and improving their sintering capacity. Hence they are expected to contain the required oxides – deficient in the main raw materials – in fairly high concentration without introducing appreciable amounts of harmful oxides such as K_2O.

These corrective components may include sand (to increase the silica); iron oxide or bauxite (to increase the alumina especially in special types of cement) and china clay (to minimize the iron in white cement). Calcium fluoride and Calcium Sulphate are useful in lowering the temperature required for a given combination of raw materials and may yield an improved quality. Table 1 show limiting values of the chemical composition of cement raw material used in cement production.

Table 1: Limiting values of chemical composition of cement raw materials

Oxide	Limiting Values (M %)	Content (M %)
CaO	60 – 90	65
SiO_2	18 – 24	21
Al_2O_3	4 – 8	6
Fe_2O_3	1 – 8	5
MgO	< 5.0	2
K_2O, Na_2O	< 2.0	1
SO_3	< 3.0	1

Overview of the Selected Cement Plant

The selected cement plant is located in the south – western part of Nigeria. It is a wet process cement plant with total installed capacity of 1,000,000 metric tonnes and was established in 1978. It has two units of operation in its quarry and crushing section, three units of operation in its raw grinding section, two units of operation in its burning and cooling section and two units of operation in its cement grinding mill. The cement plant accounts for over 40% of total local production of cement in Nigeria and has maintained consistently a production utilization capacity of over 80%. A five year data (2001 – 2005) derived from the cement plant was used for the study

THEORITICAL FRAMEWORK

Energy Analysis

The study utilized the Input – Output Energy Analysis (IOEA) approach that is a specific application of the economic Input – Output Analysis (IOA) method to estimate the Embodied Energy Intensity of the raw material preparation process of the selected cement plant.

Embodied energy is the quantity of energy required by all the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in supporting functions i.e. direct plus indirect energy. The components of embodied energy are the manufacturing, the transportation and the disposal energy required to make a material. It has nothing to do with the internal energy of the material. An embodied energy analysis involves the enumeration or measurement of the direct and indirect energy required by all the activities associated with a production process.

The Input – Output Analysis (IOA) method is a planning and forecasting modelling technique used in economic research since its introduction by Leontief (1941)[2] and has been adapted to analyze energy and labour intensities [3]. The IOEA is a specific application of the IOA method. It was developed in the 1970's through the pioneering work of Wright (1974)[4], and Bullard and Heredeen (1975)[5], while a latter overview of the energy analysis method was made by Peet(1993)[6]. The objective of the IOEA is the calculation of energy intensities.

The structure of the Input – Output Energy Analysis (IOEA) model, a large linear network, remains the same for any variable. Initially the economy must be disaggregated into J major sectors, each producing a unique good or service and each characterized by a node in the network equations. Figure 1 shows the energy flows entering and leaving each sector.

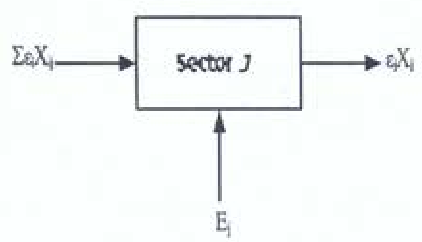

Figure1: Energy balance for a producing Sector

Energy 'embodied' in outputs from other sectors enters at the left and can be expressed as $\epsilon_i Xij$ energy intensity of product *I*

(ϵ_i) times the input of sector i to sector j (X_{ij}). Energy embodied in the sector's output is shown at the right and is expressed as the product of the energy per unit of sector J output (ϵ_j) and its output (X_j). If in figure 1, sector J denotes the energy sector, a non – zero amount E_j is extracted from the earth. The energy balance equation becomes:

$$\Sigma \epsilon_i X_j + E_j = \epsilon_j X_j. \qquad (1)$$

In matrix notation, The Energy Balance is

$$\epsilon A + E = \epsilon X \qquad (2)$$

Where **X** is a diagonalised matrix of sector outputs. This set of n equations can be solved for the n unknowns, $\in$.

For a typical product j, the production technology is represented by a vector **A**, where a typical element A_{ij} represents the amount of product i needed directly to produce a unit of project j. The n X n matrix **A** then provides a linear representation of the technology of producing all goods and services in the economy.

Solving for the energy intensity, ϵ

$$\epsilon = e(I - A)^{-1} \qquad (3)$$

Where e is a unit vector that defines the energy sector row of **(I -A)**$^{-1}$ as the energy cost of goods and services and I is the identity matrix. In IOEA e represents the direct energy intensity vector and **(I -A)**$^{-1}$ represents the Leontief inverse matrix. Thus the energy intensity vector is the matrix product of the direct energy intensity vector and the Leontief inverse matrix. The Energy Intensityϵ, or the energy embodied in one unit of production represents the total (direct plus indirect) energy requirements of output of a unit of product from sector j for final demand consumption.

Energy input – Output analysis requires formation of a table of direct energy flows to all sectors of the economy. Such data are useful in cross sectional analysis of energy consumption by sector or as data points for industrial input studies using time series data. In this study, the raw material preparation process has been divided into an economy consisting of three producing sub – sectors. These three sectors, their functions and notation are listed in table 2 below.

Table 2: Sub – division of the raw material preparation process

SECTOR	FUNCTION	NOTATION
Sector 1	Quarry Section	QS
Sector 2	Crushing Section	CS
Sector 3	Raw Grinding Section	RGS

This three sub – sector structure resulting in a 3x3 matrix equation was used to estimate the embodied energy in the raw material preparation section. Also the energy intensity model of the IOEA method, which is an adaptation of equation (3) was used for the estimation of the embodied energy at the raw material preparation stage and is stated as follows:

$$\varepsilon = D^T (I - A)^{-1} \qquad (4)$$

Where ε is the Embodied Energy, D^T is the Direct Energy Intensity Vector, A is the Technological Matrix and I is the identity Matrix

The Direct Energy Intensity vector D^T is defined as:

$$D^T = \frac{TEUS}{TQPS} \qquad (5)$$

Where TEUS is the Total Energy Used in the sector and TQPS is the Total Quantity Produced in the sector. D^T is a 1 x 3 matrix.

The Technological matrix (A) is a 3 x 3 matrix and is a ratio of the input to a sector divided by the output of the sector transferred to another sector and it is expressed as follows:

$$A_{ij} = \frac{X_{ij}}{X_j} \qquad (6)$$

Where X_{ij} is the Input and X_j is the output.

Exergy Analysis

In Exergy Analysis, three forms of exergy transfer are usually considered, these are: exergy transfer with work interaction, heat and mass interaction. This is represented mathematically as follows (Costa et al, 2001)[7]:

$$B = U + P_o + T_o S + \sum u_i n_i \qquad (7)$$

Where B is exergy, U is the internal energy, P is the pressure, T is the temperature, S is the entropy, u_i is the chemical potential and n_i the number of moles. The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system. The work done in a process depends on the initial state, the final state, and the process path. That is,

$$\text{Work} = f(\text{initial state, process path, final state}) \qquad (8)$$

In an exergy analysis, the initial state is specified, and thus is not a variable. Moreover, in conducting exergy analysis, two forms of equilibrium are considered, the environmental state (restricted dead state) and the dead (unrestricted) state. The environmental state is a restricted equilibrium where mechanical and thermal conditions are satisfied. The dead state is an unrestricted equilibrium where mechanical, thermal and chemical potential conditions are satisfied.

The first step in an exergy analysis is to determine the exergy balance of a process or a system. This exergy balance is depicted in equation (9)

$$B_{input} = B_{product} + B_{losses} + B_{waste} \qquad (9)$$

The exergy losses are mainly due to irreversibilities while the exergy of waste includes the exergy of solid and liquid waste, and air emissions. The useful exergy is the exergy of the products. This can be calculated from the exergy balance as,

$$B_{product} = B_{input} - B_{losses} - B_{waste} \quad (10)$$

The **Process efficiency or efficiency of energy use** is defined as the percentage of the useful exergy to the total input exergy:

$$\emptyset_p = \frac{B_{product}}{B_{input}} \quad (11)$$

Where $\emptyset_p$ is the exergetic efficiency.

Three forms of energy are utilized in the raw material preparation stage of cement production. The first is the use of explosives for the removal of the overburden and the blasting of the limestone deposits., the second is the use of petrol (PMS)/diesel (AGO) by the trucks for the conveyance of the blasted limestone to the crushing plant, while the third is the use of electricity by the crushing plant equipments for the reduction of the stones in the primary and secondary crushers. It is these three energy forms that contributed to the exergy inputs, exergy wastes and exergy emissions of the cement plant under consideration.

There are two forms of chemical explosives used in the cement plant under consideration; these are the Low and High explosives. The low explosives are used chiefly as propellant which is used for blasting soft rocks/ overburdens and producing of large pieces. The common low explosive used by the cement plants under consideration is ANFO (Ammonium Nitrate Fuel Oil). ANFO is a chemical compound, which is a 94% by 6% mixture of Ammonium Nitrate and Diesel Oil. The chemical formula for ANFO is $C_{0.365}H_{4.713}N_2O_3$.

The high explosives are used as detonators; they are used in the quarry for producing limestone rocks in small pieces. The common high explosive used in the cement plant under consideration is Nitro-glycerine with the chemical formula $C_3H_5(NO_3)_3$.

Exergy Input

The total exergy input for this sector is the summation of the exergy input derived from: the work potential of the explosives, the chemical exergy of the fuel combustion process of the conveying trucks and the exergy input of electricity from the crushing plant.

The total exergy input is represented mathematically as:

$$B_{input} = B_{explosives} + B_{fuel} + B_{electricity} \quad (12)$$

For electrical energy, the exergy content is as large as the energy content; hence the exergy input from electricity for the sector is the same value as the energy content of the total electricity consumed. The exergy input from the fuel combustion in the trucks was evaluated using the energy content of the fuels: Petrol (29MJ/litre) and Diesel (40.9MJ/litre).

The work potential for the explosives is determined in three steps. These are: the determination of the chemical equation that results from the explosive reaction, the determination of the energy released during the process (the heat of formation) and the determination of the work potential or exergy input using steps 1 and 2.

The chemical equation that results from the explosive reaction is determined by the use of the table of Order of priority of explosion and is stated below.

Table 3: Order of Priorities for Explosive Reactions

PRIORITY	COMPOSITION OF EXPLOSIVE PRODUCTS OF DECOMPOSITION
1	A metal and chlorine metallic chloride (solid)
2	Hydrogen and Chlorine HCl (gaseous)
3	A metal and Oxygen Metallic oxide (solid)
4	Carbon and Oxygen CO (gaseous) $C + O \rightarrow CO$
5	Hydrogen and Oxygen H_2O (gaseous) $2H + O \rightarrow H_2O$
6	CO and Oxygen CO_2 (gaseous) $CO + O \rightarrow CO_2$ (CO comes from 4)
7	Nitrogen N_2 (elemental)
8	Excess Oxygen O_2 (elemental)
9	Excess Hydrogen H_2 (elemental)

Source: Explosive Materials (www.wikepedia.com)

ANFO is expressed in equation (13) and Nitro-glycerine in equation (14)

$$C_{0.365}H_{4.713}N_2O_3 \rightarrow 0.365CO + 2.357H_2O + N_2 + 0.1392O_2 \quad (13)$$

$$C_3H_5(NO_3)_3 \rightarrow 3CO_2 + 2.5H_2O + 1.5N_2 + 0.25O_2 \quad (14)$$

Using the table of heat of formation of various substances of explosion, the heat of explosion of ANFO and Nitro-glycerine were determined as 7.144kJ/g and 6.380kJ/g respectively. The value of the heat of formation derived represents the energy expended during the blasting process. The table of heat of formation of various substances is shown below:

Table 4: Heat of formation of various substances

NAME OF SUBSTANCE	FORMULAR	MOLECULAR WEIGHT (g/mol)	ΔE_f (kJ/mole)
Carbon Monoxide	CO	28	-111.8
Carbon dioxide	CO_2	44	-393.5
Water Vapour	H_2O	18	-240.6
Nitro-glycerine	$C_3H_5N_3O_9$	227	-333.66
RDX	$C_3H_6N_6O_6$	222	+83.82
HMX	$C_4H_8N_8O_8$	296	+104.77
PETN	$C_5H_8N_4O_{12}$	316	-514.63
TNT	$C_7H_5N_3O_6$	227	-54.39
TETRYL	$C_7H_5N_5O_8$	287	+38.91

SOURCE: Explosive Materials (www.wikepedia.com)

The potential of an explosive is the total work that can be performed by the gas resulting from its explosion, when expanded adiabatically from its original volume, until its pressure is reduced to atmospheric pressure and its temperature 15°C. The potential is therefore the total quantity of heat given off at constant volume when expressed in equivalent work units and is a measure of the strength of the explosive.

The conversion of energy to work in the constant pressure state is expressed as:

$$Q_{mv} = Q_{mp} + W \quad (15)$$

Where Q_{mv} is the total heat given off by a mole of explosive at 15^{0}C and constant volume; Q_{mp} is the total heat given off by a mole of explosives of 15^{0}C and constant pressure (atmospheric) and W is the work energy expended in pushing back the surrounding air in an unconfined explosion.

Using the principle of the initial and final state and heat of formation table (table 3), the heat released at constant pressure Q_{mp} may be readily calculated. The work energy expended W by the gaseous products of detonation is expressed by:

$$W = P\,dv \qquad (16)$$

With pressure constant and negligible initial volume, this expression reduces to:

$$W = P.\ V_2 \qquad (17)$$

By applying the appropriate conversion factors, work is determined in units of MJ/kg as:

$$W = \frac{(0.572)(Nmol)(4185J/kcal)(10^3)g/Kg(1mol)}{10^6(MWg)}$$

MJ/kg (18)

Where MW is the Molecular Weight, kcal = Kilocalories, Nmol = Number of moles and mol = moles

Based on equation (18) the work expended in pushing back the surrounding air during the explosion of ANFO and Nitro-glycerine was determined as 0.1086 MJ/kg and 0.0765 MJ/kg respectively. The total exergy input for the explosives was evaluated using equation (15) and this was determined as 7144.11MJ/kg for ANFO and 6380.8 MJ/kg for Nitro-glycerine.

Exergy Losses

Exergy losses in the quarry and crushing section come from the gases which are emitted as products of the detonation and deflagration of ANFO and Nitro-glycerine, however the water vapour emitted by the explosives are absorbed by the quarried limestone.

The quantities of the various gases lost are estimated from the chemical explosion balanced equations (13and 14), while the physical exergy lost is estimated using the following equations:

$$B_{ph} = C_p(T - T_o) - T_o\left(Cp\ln\frac{T}{T_o} - R\ln\frac{P}{Po}\right) \qquad (19)$$

This equation can be expressed in terms of its thermal and pressure component as

$$B_{ph} = C_p\left(T_1 - T_0 - T_0 In\frac{T_1}{T_0}\right) + RT_0 In\frac{P_1}{P_0} \qquad (20)$$

Since the explosion is at constant pressure, the pressure component is omitted and for the quarry and crushing section, only the thermal component is considered. Thus reducing the equation in this section to:

$$B_{ph} = C_p\left(T_1 - T_0 - T_0 In\frac{T_1}{T_0}\right) \qquad (21)$$

Environmental Impact

The raw material preparation process emits two major green house gases carbon monoxide (CO) and Carbon dioxide (CO_2) during the blasting operations as seen in equations (13) and (14), when explosives, both high and low are used to dislodge the limestone from their natural rock formations.

RESULTS AND DISCUSSIONS

Table 5 shows the data inputs, while table 6 shows the results obtained from the study

Embodied Energy Intensities

From table 3 and 4, it can be seen that for the cement plant under consideration, a 6% reduction in electricity consumption between 2001 and 2002, resulted in a favourable decrease of 18% in the embodied energy intensity for raw material preparation during the same period. Also a further reduction in electricity consumption of 30% over the period 2002 – 2005, resulted in a total reduction of embodied energy intensity of 18% from 74.78 – 60.88 kWh/t. In an overall sense, the cement plant witnessed a total reduction of embodied intensity of 30.86kWh/t or 34%, from an electricity consumption reduction of 12,838Mwh.

Exergy Efficiency

The exergic efficiency over the five year period showed an improvement of 4%, in the period 2001 – 2005, the exergy efficiency improved from 45% to 49.8% in 2004, in 2005 there was a drop in efficiency by 2% from 49.8% to 47.4%. Even though there was improvement in overall exergic efficiency of the plant over the period, this was below the 50% optimum best practices level recommended [8].

The result of the embodied energy intensity and the exergic efficiency even though favourable shows that there is still room for improvement. The recorded embodied intensity for the plant during the period 2001 – 2003 was in the range of 60.88 – 91.74kWh/t, this is over 70% higher than the best recommended global practice of 18 – 20kwh/t [9]. This means that the energy efficiency programme of the plant which has yielded some results needs to be further intensified to achieve the 70% energy saving capability.

Environmental Impact

From table 4, it can be seen that the cement production activities of the plant under review still impacts negatively on the environment with the emission of CO_2 and CO gases. However the results show that there was a reduction in the emission of over 20% in this green house for the period under review. For the period 2001 – 2005, CO_2 emission decreased from 95.8 T CO_2 to 66.2 T CO_2. Similarly the CO emission decreased from 25.9 T CO to 16.4 T CO.

Table 5: Data Input Used in the study

	YEARS				
Quantities	2001	2002	2003	2004	2005
Total operating Hours (hrs)	8760	8760	8760	8760	8760
Electricity Consumed (Mwh)	37696	35571	32746	32685	24858
Electricity consumed (GJ)	135706.5	128055.6	117885.6	117666	89488.8
Petrol (PMS) (litres)	509552	454812	466579	441489	461900
Petrol (PMS) (GJ)	14777.01	13189.55	13530.79	12803.18	13395.10
Diesel (AGO) (litres)	6075858	3809291	3486326	1971335	2385116
Diesel (AGO) (GJ)	248502.59	155800	142590.73	80627.60	97551.24
Explosives (ANFO) (kg)	216062	218925	193800	149970	136370
Explosives (Nitro-glycerine) (kg)	164870	194550	178075	140175	113950

Table 4: Embodied Energy Intensity, Exergy efficiency and Greenhouse gas emissions

	YEARS				
Quantities	2001	2002	2003	2004	2005
Embodied energy intensity (kwh/t)	91.74	74.78	75.89	57.55	60.88
Exergy Efficiency $\varnothing_p$ (%)	45.5	48.7	49.4	49.8	47.4
Carbon dioxide (CO_2) (kg CO_2)	95789.47	113033.55	103461.58	81441.68	66204.95
Carbon monoxide (CO) (kg CO)	25927.44	26271	23256	17996.4	16364

SUMMARY AND CONCLUSION

The study considered the energy and exergy analysis of the raw material preparation of a prominent wet process cement plant located in the south – western part of Nigeria. Energy analysis was used to estimate the embodied energy intensity of the raw material preparation while exergy analysis was used to estimate the exergic efficiency and the environmental impact of the raw material preparation process. Based on the results obtained from energy analysis, the study showed that there was improvement in the embodied energy intensity obtained for the period under review, however the study showed that there was a 70% energy improvement potential of the raw material preparation process. The study also showed that even though there was a marginal improvement in the exergy efficiency of the process, this has not reached the 50% optimum level recommended. The study also showed that CO and CO_2 were the two major green house gases emitted during the process and there was a marked reduction of 20% in their emission during the period under review.

The study concluded by recommending that the energy efficiency programme which has resulted in the improvement of all the indicators measured should be intensified as there is 50 – 70% energy improvement potential in the raw material preparation process of the plant.

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